

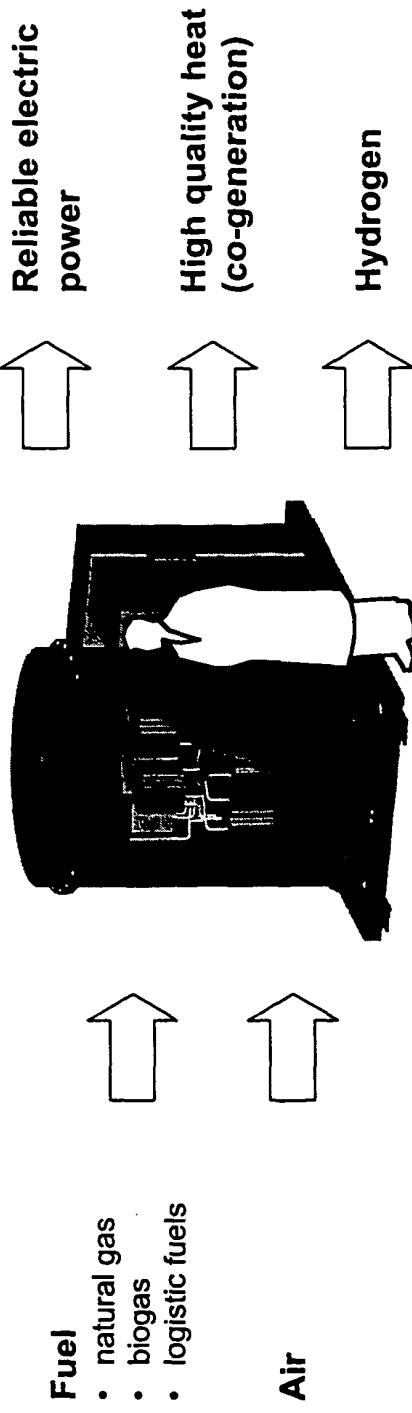
Ion America

Co-production of hydrogen and electricity from an SOFC generator

April 2003

Can hydrogen and electricity be co-produced economically?

**Ion America's 100 kWe
SOFC generator**



Distributed generation model – point of use production eliminates the cost of T&D

Hydrogen for Transportation

Factors

- Lack of hydrogen infrastructure makes refueling fuel cell vehicles (FCV's) difficult.
- Distribution from centralized plants not economical.

Hydrogen Production

- Water electrolysis is clean (if renewable sources used), but too expensive.
- Decentralized reforming plants for H₂ may be economical.

Many potential users will have requirements for both hydrogen and electricity

- industrial complexes
- product distribution warehouses
- multi-unit housing

SOFC Hydrogen and Electricity Generation

Solid oxide fuel cells (SOFC) produce hydrogen during electrical power generation.

Within a SOFC stack, we have

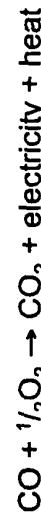
steam methane reforming:



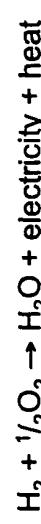
water-gas shift:



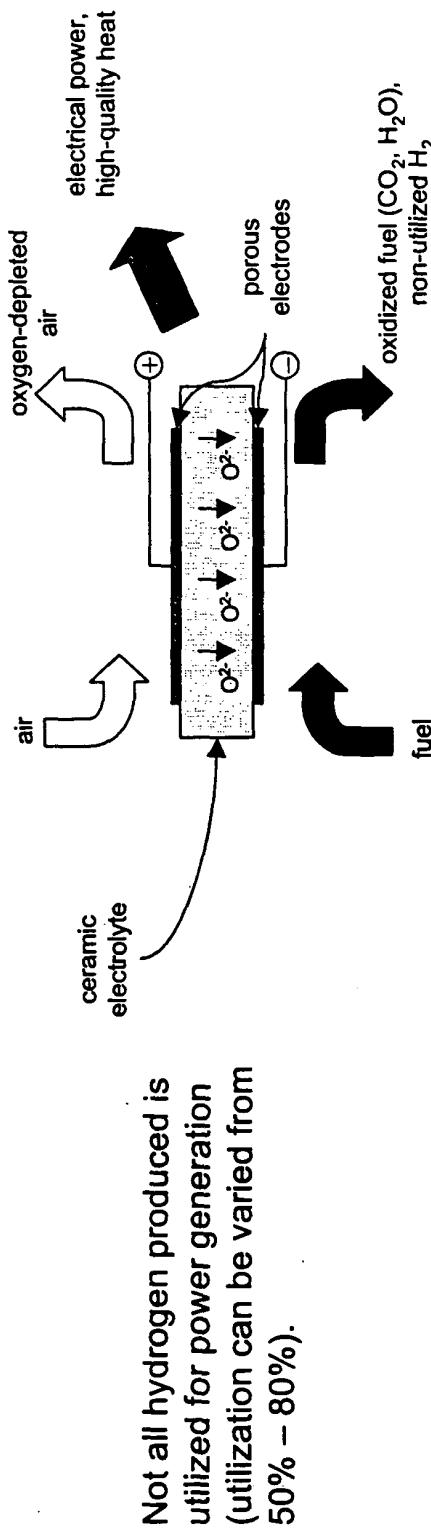
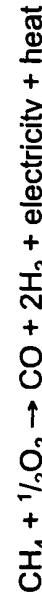
CO oxidation:



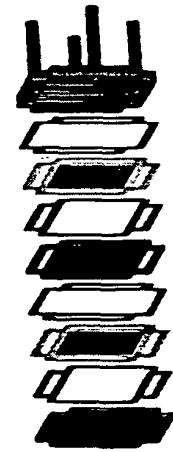
hydrogen oxidation:



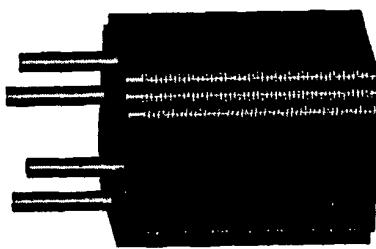
partial oxidation:



Ion America's SOFC Product



Fuel cells are stacked together with separator plates (interconnects) and seals to attain the required power output.



A 10 kW modular SOFC stack.

100 kW SOFC-HDHP modular system.
Has 10 SOFC stacks.

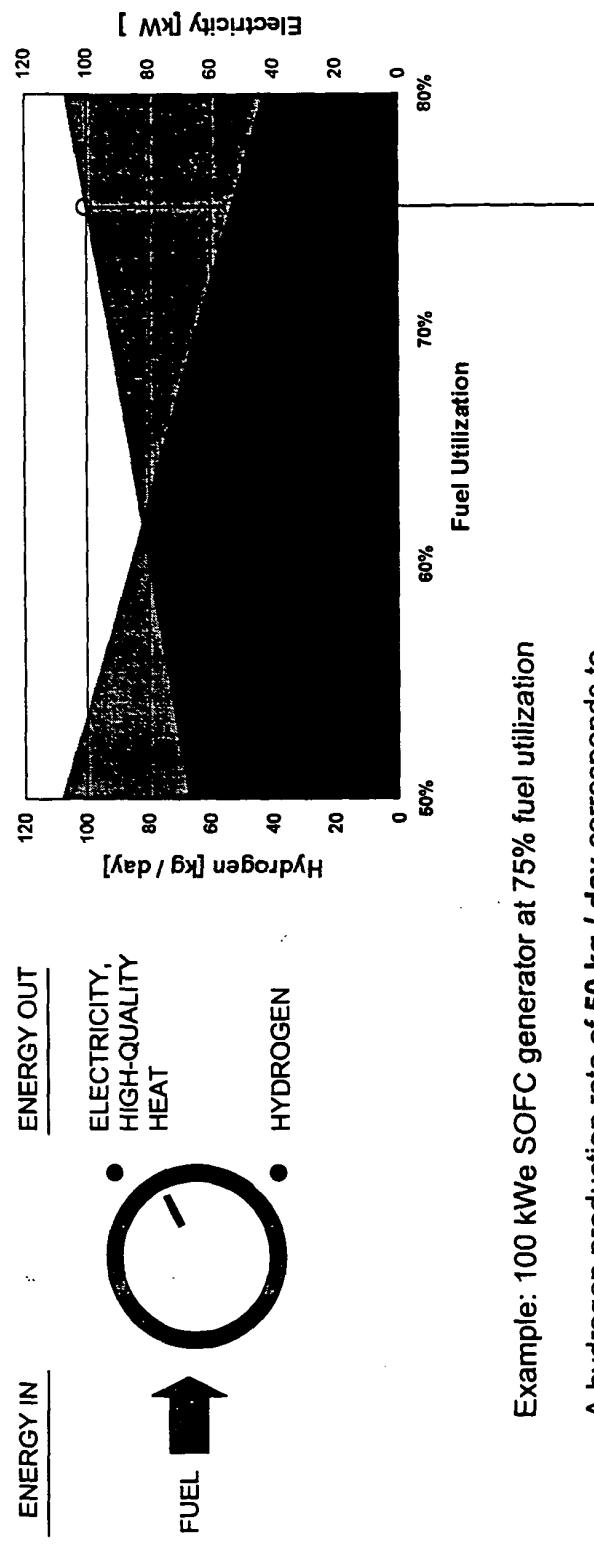
Easily configured for other sizes.

Modular design for increased reliability.

Hydrogen and Electricity Availability

Rate of electricity and hydrogen production as a function of fuel (methane) utilization, total fuel flow held constant.

**Electricity and hydrogen co-production
at constant fuel flow**



Example: 100 kWe SOFC generator at 75% fuel utilization

A hydrogen production rate of 50 kg / day corresponds to _____

- a gasoline energy equivalent of 47 gallons / day (equal energy basis)
- support for a fleet of 80 fuel cell vehicles

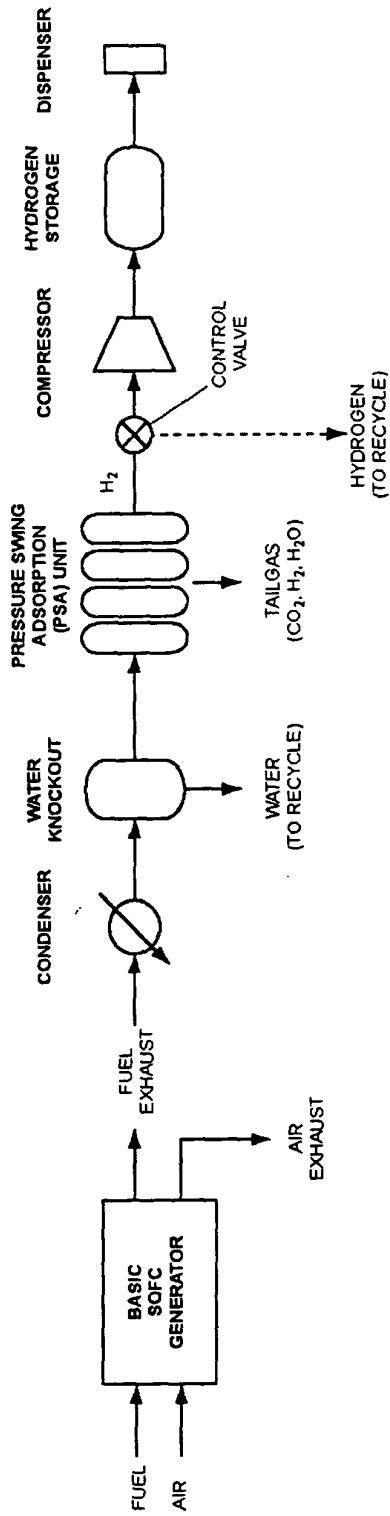
Cost of Production

Approach

- Start with Ion America's basic 100 kW_e generator and cost of electricity calculation
 - No gas recycle
 - No co-generation
- Add detailed model for hydrogen processing in order to produce a 7000 psi product
 - Equipment selection, sizes, and costs estimated from Directed Technologies Inc., "Cost and performance comparison of stationary hydrogen fueling appliances," Task 2 Report to U.S. DOE, April 2002.

Simplified Flow Diagram

- The basic SOFC generator is cost-modeled elsewhere.
- Hydrogen storage at 7000 psi is sized for one day's worth of production.
- Other hydrogen separation and compression components sized for maximum production capacity.
- Fuel utilization controlled at the generator.



Two Scenarios

For both scenarios, the SOFC plant generates a constant 100 kW_e.

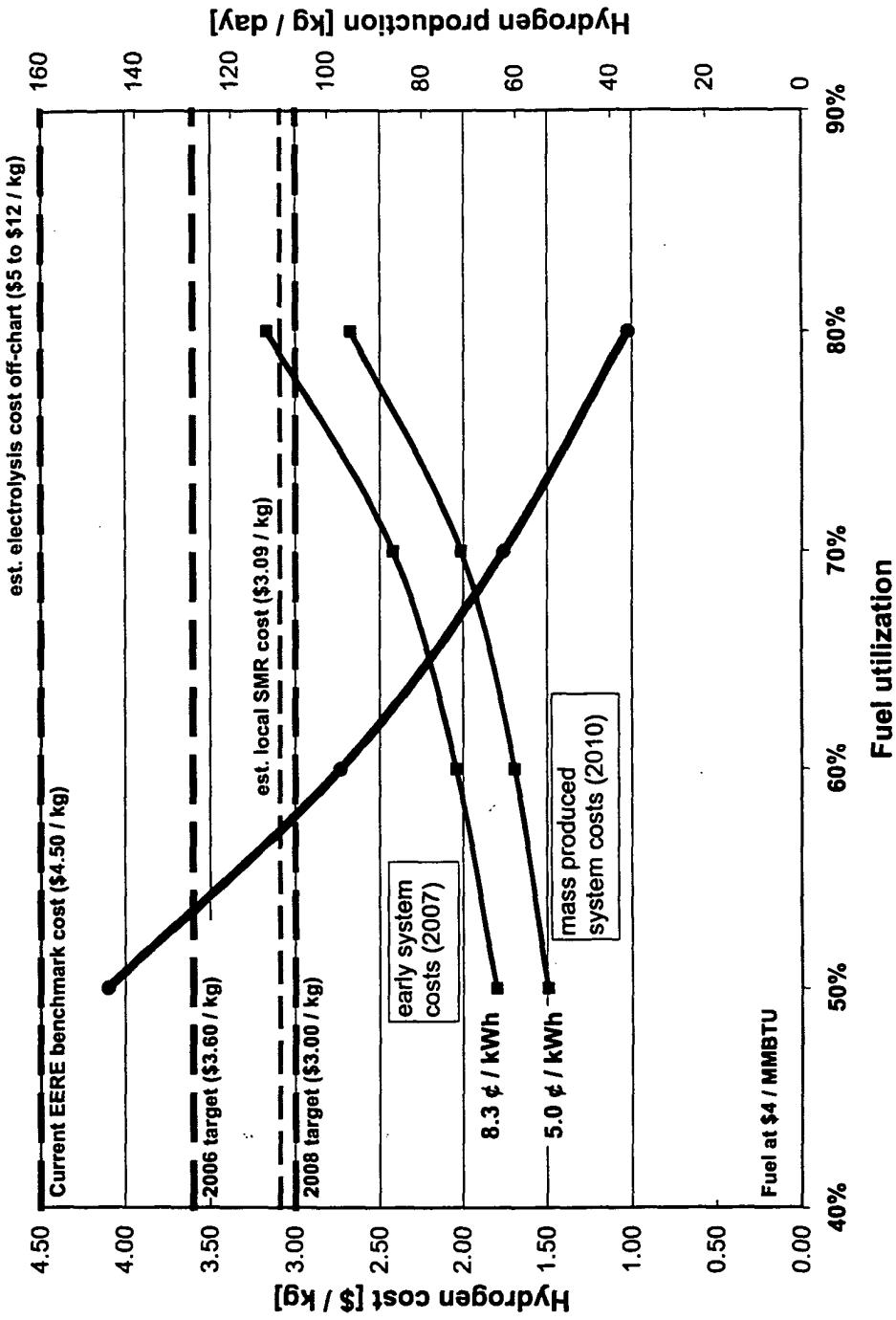
Case 1 (2007)

- Early Ion America SOFC product at \$1,400 / kW capital equipment.
- Natural gas fuel at \$4 / MMBtu
- High O&M costs
 - \$0.01 / kWh for SOFC
 - 20% of compressor cost
 - 5% of balance of separation system cost

Case 2 (2010)

- Mass-produced Ion America SOFC product at \$400 / kW capital equipment
- Natural gas fuel at \$4 / MMBtu
- Reduced O&M costs
 - \$0.005 / kWh for SOFC
 - 10% of compressor cost
 - 2% of balance of separation system cost

Hydrogen Production Metrics per 100 kW Electricity Generated



Sample Calculation and Assumptions

“Case 1” point at 60% utilization

SOFC Electricity Generation		SOFC H2 Production		Ion America H2 system		Supporting calculations for H2 production	
SOFC Assumptions		H2 Production Assumptions					
Capital Costs [\$/kW]	1,400	Base Equipment	88,801				
Heat Rate [Btu/kWh]	8,530	Mfr Markup	13,320				
O&M Cost [\$/kWh]	0.01	Miscellaneous	8,880				
Amortization Period [y]	8.3	Total capital equipment	111,001				
Capacity Factor [%]	90%						
Energy Production Costs in \$ / kWh		Equipment life [y]	10				
Cost of capital	1.8	Capacity [kg H2/y]	29,188				
Depreciation	2.1						
Fuel Cost	3.4	H2 Productions Costs in \$ / y					
O&M Cost	1.0	Depreciation	11,100				
		Cost of capital	11,100				
		Compressor O&M	4,000				
		Other O&M	3,440				
		Process gas (SOFC effluent)	14,741				
		Electricity (from SOFC generator)	15,000				
Electricity Cost [\$/kWh]		Total annual cost [\$/y]	59,382				
		Hydrogen cost (\$ per kg)	2.04				
		Gasoline equiv. cost (\$ per gal)	2.16				
Basic Assumptions							
Fuel cost [\$/MMBTU]	4.00						
Cost of capital	10%						
SOFC conversion efficiency	40%						

Comparison to Steam Methane Reforming and Electrolysis

At about **\$2.00 / kg**, the estimated cost of **SOFC-produced hydrogen** is well under the costs using other approaches.

- Hydrogen produced by local **steam methane reforming** is estimated to cost **\$3.09 / kg**.¹
- Estimates for cost of hydrogen produced by **water electrolysis** ranges from 1.5² to 3.6³ times the cost of steam methane reforming, or **\$5.00 to \$12.00 / kg**.

1. Directed Technologies Inc., "Cost and performance comparison of stationary hydrogen fueling appliances," Task 2 Report to U.S. DOE, April 2002. Cost adjusted for natural gas pricing at \$4 / MMBTU.
2. Stuart Energy USA, "Filling up with hydrogen 2000," Proceedings of the 2002 U.S. DOE Hydrogen Program Review, 2002 (with electricity at \$0.075/kWh).
3. B. Eliasson and U. Bossel, ABB Switzerland white paper, January 2003.

Conclusion

- Large consumer base will exist for generation of electricity and hydrogen at point-of-use.
- Hydrogen production can be added at relatively low capital cost to Ion America's SOFC generators.
- Ion America's SOFC-based approach is cost-effective and will have market entry by 2007.

Co-production of hydrogen and electricity from an SOFC generator

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Hydrogen for transportation

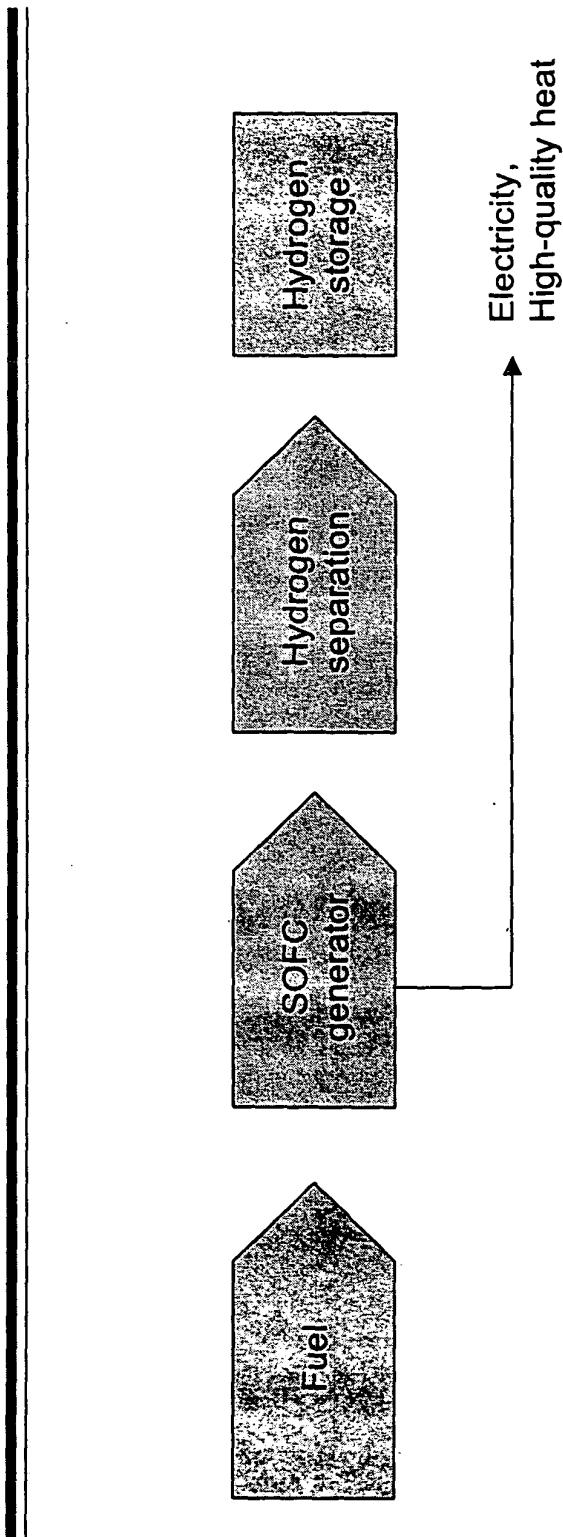
Factors

- Lack of hydrogen infrastructure makes refueling fuel cell vehicles (FCV's) difficult.
- Existing natural gas pipelines from centralized plants have compatibility, capacity issues.
- Truck transportation from centralized plants not economical.
- Water electrolysis is clean (if renewable sources used), but expensive.
- Studies show that small, decentralized plants based on reforming can be economical.
- Many potential users would have demand for both hydrogen and electricity (fleets, apartment complexes, manufacturers, etc.).

SOFC hydrogen and electricity generation

- A solid oxide fuel cell (SOFC) power generator produces hydrogen as a by-product of electricity generation. Any hydrocarbon gas can be used as fuel.
An SOFC is a power generator and fuel reformer in one package.
- The hydrogen is contained in the stack effluent.
The hydrogen can be separated and purified at no additional fuel cost.
- The fuel cost only significantly affects the cost of electricity produced, not the hydrogen.
- Can be 100% green if renewable fuel sources (e.g. biogas) are used.

Hydrogen and electricity production by SOFC



- SOFC generators produce hydrogen internally from excess fuel
- Relative amounts of electricity and hydrogen produced are easily controlled by user
- Power generation costs are competitive with centralized generation
- Efficient use of hydrocarbon fuel in SOFC results in low emissions
- Realizes full benefit of distributed generation

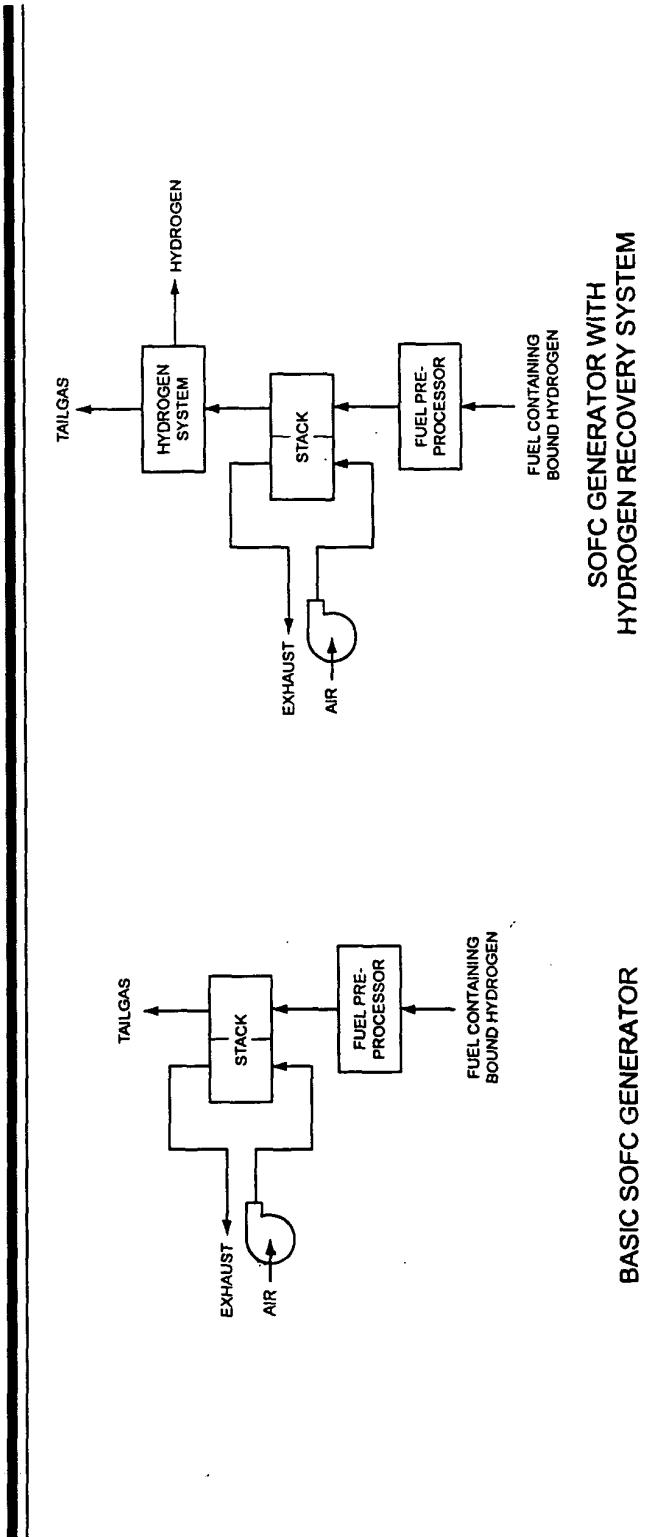
Hydrogen and electricity production by SOFC (continued)

- An Ion America SOFC generation unit operating on hydrocarbon fuel produces hydrogen as a by-product, mixed with other gases and water.
- This hydrogen might be separated from other gases and compressed.

A 100 kW_e generator leaves more than 50 kg H₂ per day in the effluent

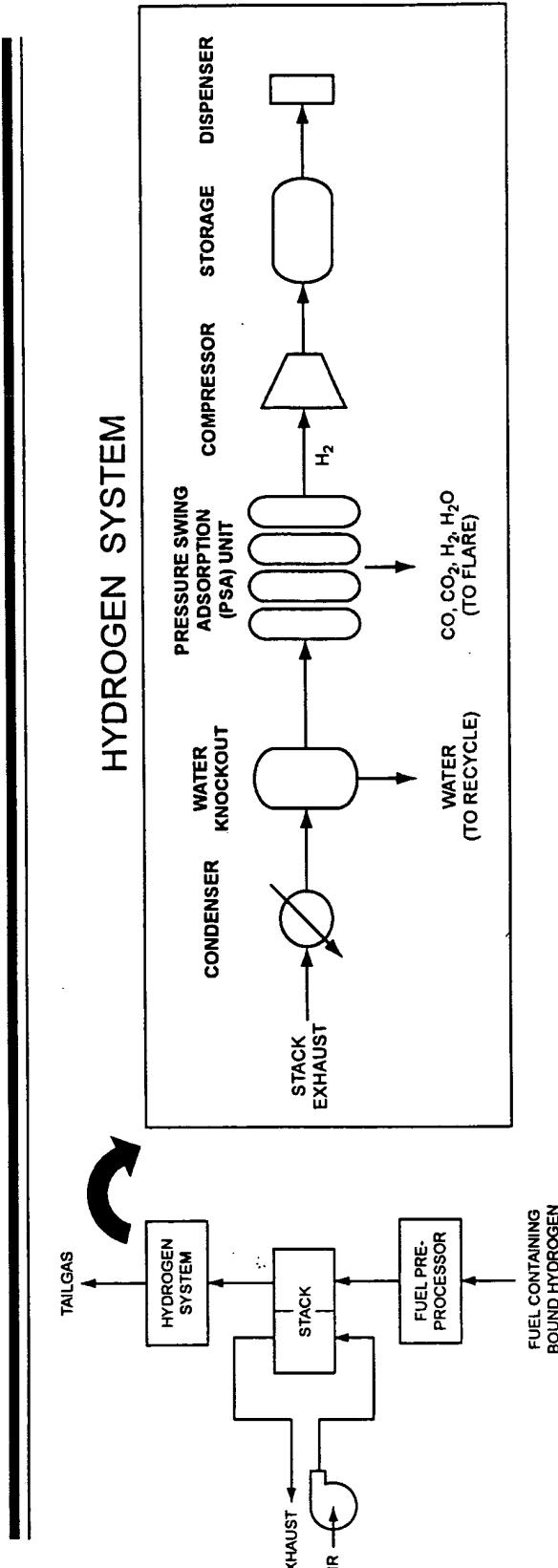
- This rate will support an 80-vehicle fleet of FCVs at 12,000 miles per year, per vehicle.
- More vehicles can be supported with additional fuel usage.

Simplified flow diagram



- SOFC generator acts as a power-generating partial oxidation and steam-methane reformer
$$\text{CH}_4 + \text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2 + \text{electricity} + \text{heat}$$
$$\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 + \text{electricity} + \text{heat}$$
- The tailgas might be used for heating/cooling, recycled, flared etc. OR the hydrogen might be extracted, compressed, and stored for use.

Hydrogen separation, compression, storage and dispensing details



- An SOFC generator already carries many components needed for hydrogen production:
 - reformer (stack)
 - blowers and pumps
 - heat exchangers
 - controllers, valves, other infrastructure
- The additional required capital equipment costs are for separation, compression, storage, and dispensing.
- The required units have been selected, sized, and costed using a detailed 2002 DOE study for decentralized steam-methane reforming stations of similar size (reference 1 on page 11).

Cost of hydrogen

A detailed capital cost model has been developed for the SOFC generator.

Capital costs start at \$1,400 / kW in 2006, fall to \$400 / kW in 2011 at full production.

Two scenarios considered in following pages:

Gasoline equivalent cost for typical FCV's

"High-cost" case

- SOFC cost of \$1,400 / kW
- fuel at \$8 / MMBtu (and correspondingly high electricity cost)
- elevated O&M costs



\$1.03 / gallon

- SOFC cost of \$400 / kW
- fuel at \$4 / MMBtu
- lower O&M costs



\$0.82 / gallon

“High cost” scenario

SOFC Electricity Generation		SOFC H2 Production		Supporting calculations for H2 production	
Ion America SOFC system		Ion America H2 system			
SOFC Assumptions		H2 Production Assumptions			
Capital Costs [\$/kW]	1,400	Base Equipment	72,000		
Heat Rate [Btu/kWh]	8,530	Mfr Markup	10,800		
O&M Cost [\$/kWh]	0.01	Miscellaneous	10%		
Amortization Period [y]	8.3	Total capital equipment	7,200		
Capacity Factor [%]	90%		90,000		
Energy Production Costs in \$ / kWh		Equipment life [y]	10		
Cost of capital	1.8	Capacity [kg H2/y], max at 15,000	15,000		
Depreciation	2.1				
Fuel Cost	6.8	H2 Production Costs in \$ / y			
O&M Cost	1.0	Depreciation	straight		
		Cost of capital	10%		
		Compressor O&M	10%		
		Other O&M	5%		
		Process gas (SOFC effluent)	0		
		Electricity (from SOFC generator)	11,000		
Electricity Cost [\$/kWh]	11.7				
Basic Assumptions		Total annual cost [\$/y]	33,600		
Fuel cost [\$/mmBTU]	8.00	Hydrogen cost (\$ per kg)	2.24		
Cost of capital	10%	Gasoline equiv. cost (\$ per gal)	1.03		
SOFC conversion efficiency	40%				

NOTES

- SOFC stack and balance-of-plant have different depreciation periods; 8.3 years is the cost-weighted system average.
- Value of high-quality heat generated by the SOFC system (co-generation) is neglected.
- H2 production assumes completion of steam methane reforming reaction and 100% water gas shift reaction.
- Capital equipment costs for hydrogen generator are estimated to match a 100 kW SOFC generator.

potential production rate [kg/d] 62

annual cost [\$/y] 9,292

allowance for electricity usage 10%

over compression 300

days of operation 100

size of generator [kW] 100

nominal fuel utilization 70%

LHV of fuel [Btu/lb] 21.518

H2 separation yield 90%

potential production rate [kg/d] 62

“Low cost” scenario

SOFC Electricity Generation		SOFC H2 Production		Supporting calculations for H2 production	
Ion America SOFC system		Ion America H2 system			
SOFC Assumptions		H2 Production Assumptions			
Capital Costs [\$/kW]	400	Base Equipment	72,000		
Heat Rate [Btu/kWh]	8,530	Mr Markup	10,800		
O&M Cost [\$/kWh]	0.005	Miscellaneous	7,200		
Amortization Period [y]	8.3	Total capital equipment	90,000		
Capacity Factor [%]	90%			Cost	
Energy Production Costs in \$/kWh		Equipment life [y]	10	Water removal	1,200
Cost of capital	0.5	Capacity [kg H2/y], max at 15,000	14,579	PSA	14,000
Depreciation	0.6			Compressor	20,000
Fuel Cost	3.4	H2 Production Costs in \$ / y		Storage	17,800
O&M Cost	0.5	Depreciation		Dispenser	18,000
	Electricity Cost [\$/kWh]	Cost of capital	10%	Assembly	1,000
		Compressor O&M	10%	Total	72,000
		Other O&M	2%		
		Process gas (SOFC effluent)	0		
		Electricity (from SOFC generator)	5,000		
Basic Assumptions					
Fuel cost [\$/mmBTU]	4.00	Total annual cost [\$/y]	26,040	compressor electricity calculation	
Cost of capital	10%	Hydrogen cost (\$ per kg)	1.79	cost basis of 3 HP for 300 SCFH	0.050
SOFC conversion efficiency	40%	Gasoline equiv. cost (\$ per gal)	0.82	SOFC electricity [\$/kWh]	3,870
				annual cost [\$/y]	
				allowance for electricity usage	
				over compression	10%
				days of operation	300
				size of generator [kW]	100
				nominal fuel utilization	75%
				LHV of fuel [Btu/lb]	21,518
				H2 separation yield	90%
				potential production rate [kg/d]	49

NOTES

- SOFC stack and balance-of-plant have different depreciation periods; 8.3 years is the cost-weighted system average.
- Value of high-quality heat generated by the SOFC system (co-generation) is neglected.
- H2 production assumes completion of steam methane reforming reaction and no water gas shift reaction.
- Capital equipment costs for hydrogen generator are estimated to match a 100 kW SOFC generator.

Hydrogen production via steam methane reforming and electrolysis

In comparison to the estimated SOFC hydrogen cost of \$1.79 to \$2.24/kg (\$0.82 to \$1.03 / gallon gasoline):

- Hydrogen produced by local steam methane reforming is estimated to cost \$3.38/kg¹
 - gasoline equivalent of \$1.55 / gallon
 - Estimates for cost of hydrogen produced by water electrolysis ranges from 1.5² to 3.6³ times the cost of steam methane reforming
 - gasoline equivalent of \$2.40 to \$5.58 / gallon
1. Directed Technologies Inc., "Cost and performance comparison of stationary hydrogen fueling appliances," Task 2 Report to U.S. DOE, April 2002.
2. Stuart Energy USA, "Filling up with hydrogen 2000," Proceedings of the 2002 U.S. DOE Hydrogen Program Review, 2002 (with electricity at \$0.075/kWh).
3. B. Eliasson and U. Bossel, ABB Switzerland white paper, January 2003.

Hydrogen production via SOFC

- Valuable by-product of low-cost SOFC electricity
- Low additional capital cost
- Hydrogen as cheap as tax-free gasoline
 - Large potential market
- No additional infrastructure
 - 100% green with renewable fuel

High Density Energy Storage with Solid Oxide Regenerative Fuel Cells

Ion America

Ion America Proprietary and Confidential

Electrical Energy Storage

High density electrical energy storage critical for several military and civilian applications.

Other storage device requirements include

- High efficiency.
- High reliability.
- Long service life.
- Low noise.
- Environmentally compatible – low emissions.
- Low thermal signature.
- Low pressure air-breathing.

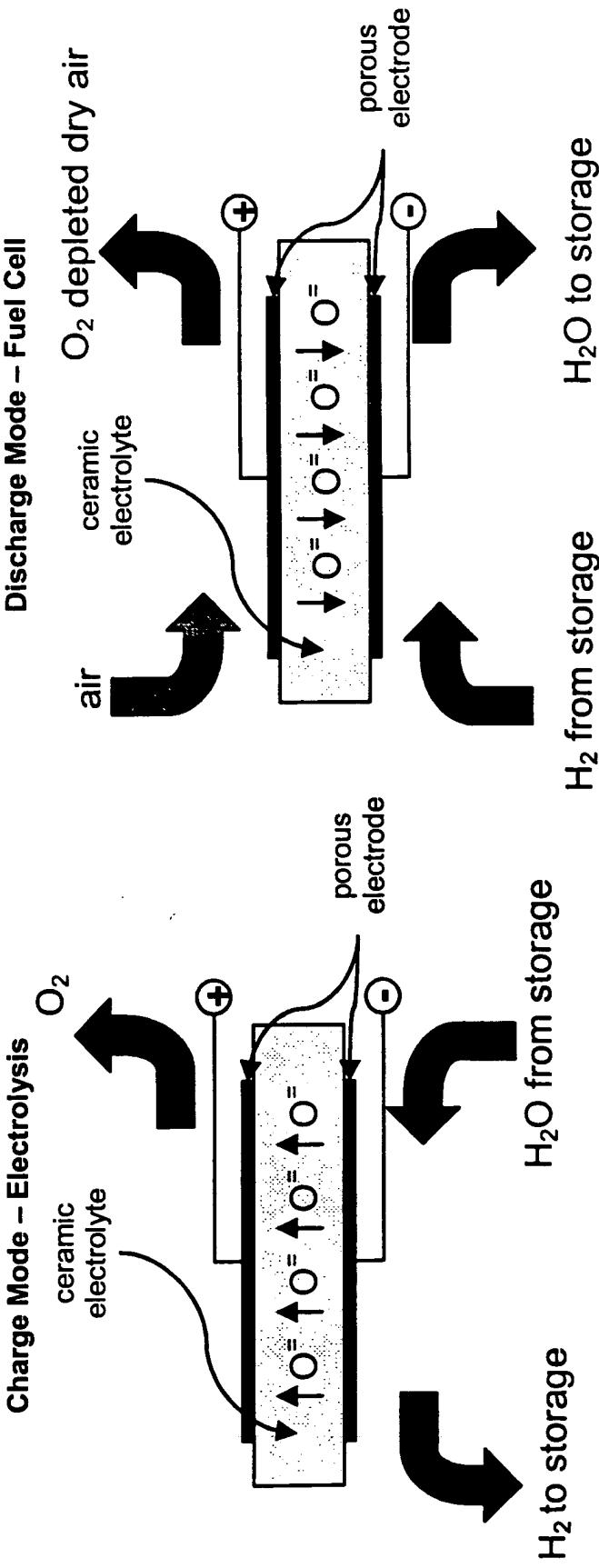
**Ion America Solid Oxide Regenerative Fuel Cells (SORFC)
meet all requirements.**

Competing Technologies

- Rechargeable batteries
 - Low energy density.
- Flywheels
 - Low energy density.
 - Vibration.
 - Gyroscopic effects.
 - Short-term operation.
- Proton Exchange Membrane (PEM) regenerative fuel cells.
 - Require storage of hydrogen *and* oxygen.
 - Difficulty breathing rarefied air.
 - Wetting and freezing issues with electrolyte.
 - Losses by diffusion through electrolyte.
 - Electrolyzer and fuel cell realized with two separate devices.
 - Low round-trip efficiency.

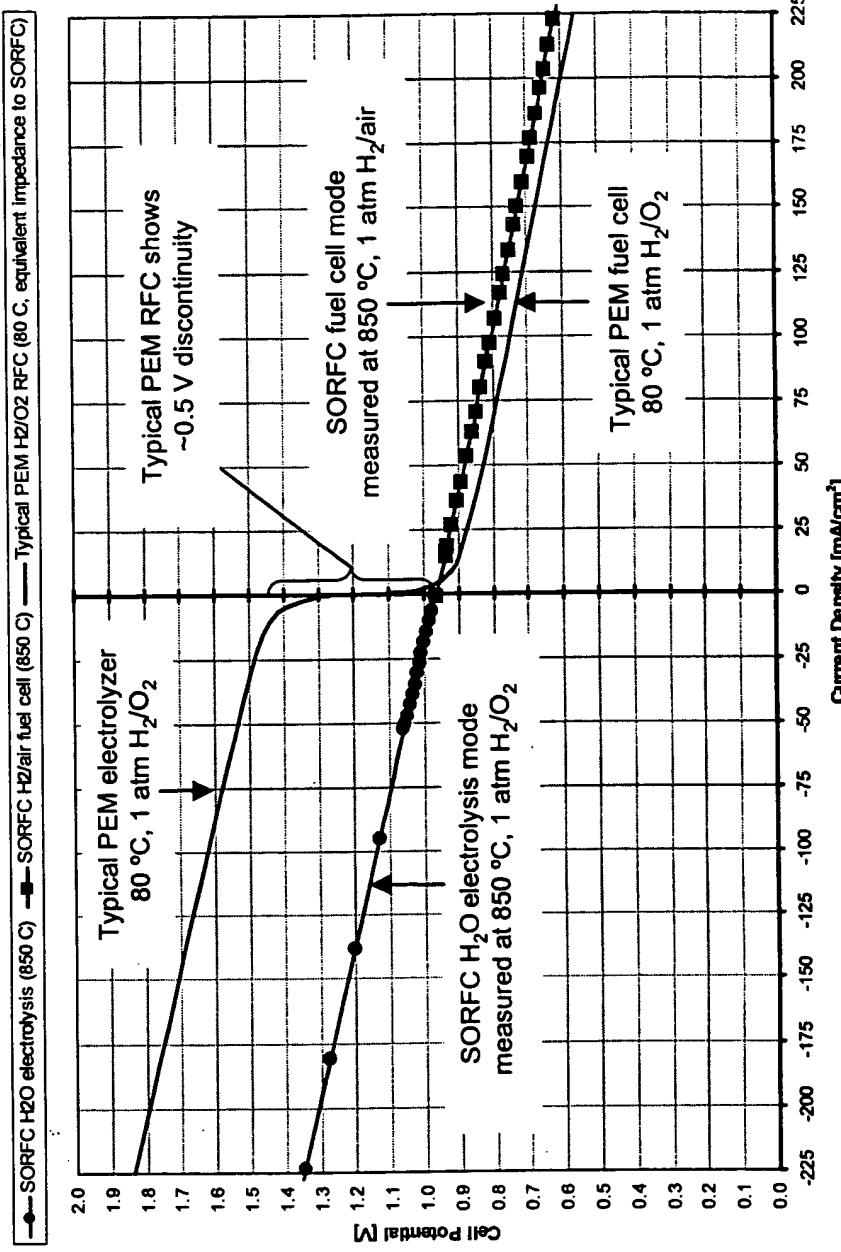
Solid Oxide Regenerative Fuel Cells (SORFC)

- Based on reversible solid oxide fuel cells.
- In charge mode the SORFC functions as an electrolyzer and regenerates hydrogen (and oxygen) from stored water.
- In discharge mode the SORFC functions as a fuel cell which generates electrical energy from hydrogen and oxygen (can be rarefied air).



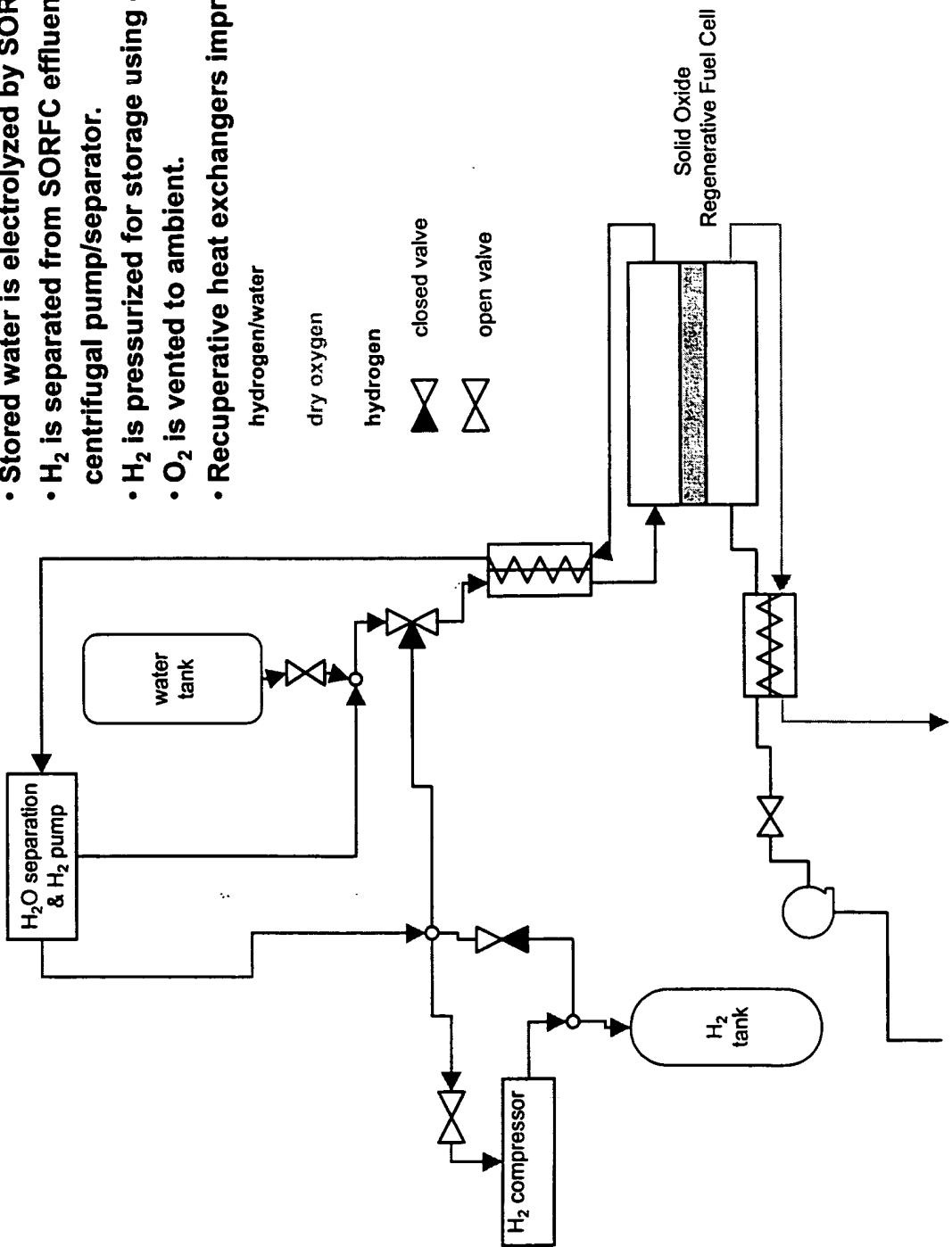
SORFC Compared to PEM RFC

- There is no measurable discontinuity in the SORFC polarization curve.
- Air-breathing SORFCs are not subject to water loss, dryout, or freezing.
- SORFCs can breathe rarified air, resulting in significantly higher specific energy compared to PEM RFCs, especially if reserves are carried.

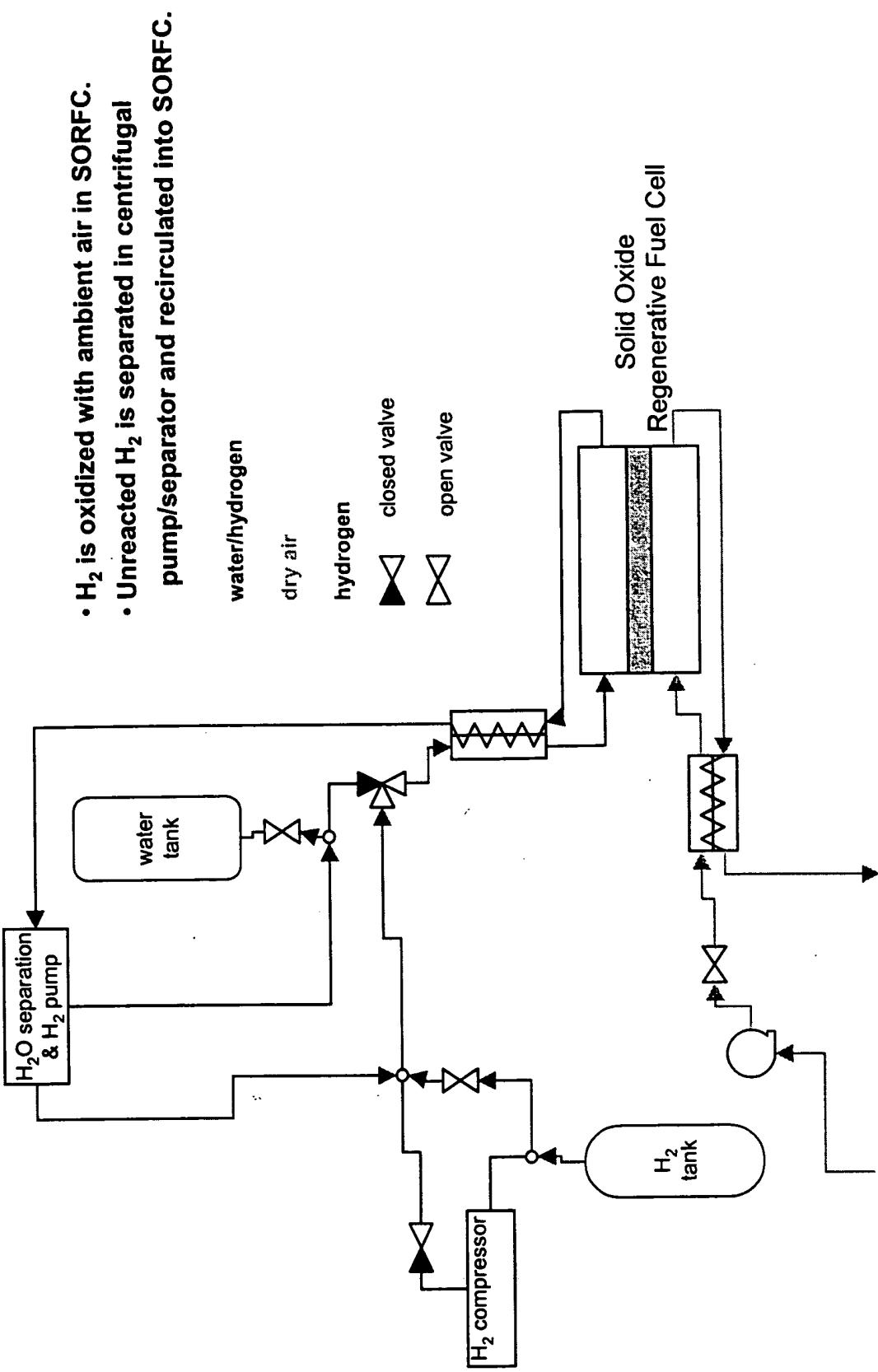


SORFC in Charge Mode

- Stored water is electrolyzed by SORFC.
- H₂ is separated from SORFC effluent with centrifugal pump/separator.
- H₂ is pressurized for storage using electrochemical device.
- O₂ is vented to ambient.
- Recuperative heat exchangers improve system efficiency



SORFC in Discharge Mode



Applications

Continuous electrical power for remote locations utilizing solar panels and regenerative solid oxide fuel cells.

Allows storage of energy at low cost periods, and consumer generation of power during high-cost periods.

- Can be combined effectively with other renewable energy sources (wind, etc.).
- High altitude airplane and airship regenerative electrical power supply.

Remote power for base stations.

- High energy density electrical energy storage for autonomous sites (communication/research/military).

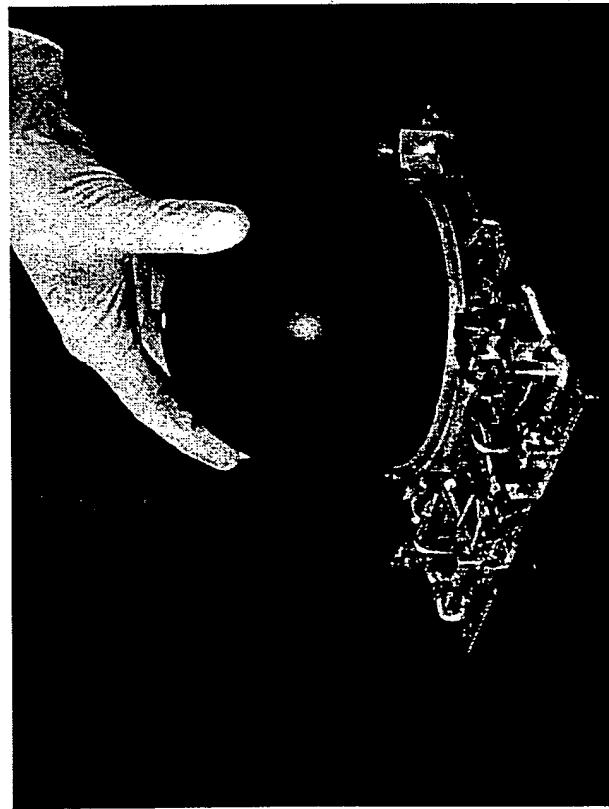
Ion America Expertise in Electrochemical Devices

- Fuel Cells for Space Flight Power.
- PEM technology for Navy applications.
- PEM technology for regenerative power systems for high altitude aircraft.
- Solid Oxide Regenerative Fuel Cells.
- Solid Oxide Electrolyzers.
- Solid Oxide Fuel Cells.
- Commercial Solid Oxide Fuel Cell systems from 10kW to 100kW.

Ion America – High Reliability Heritage

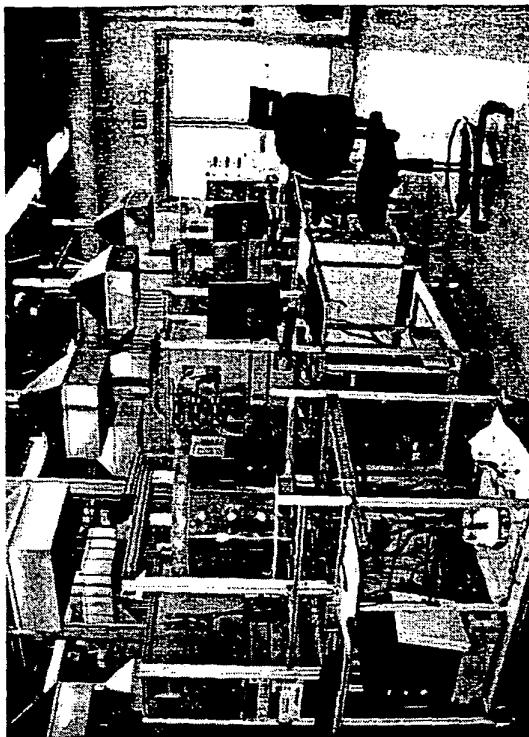
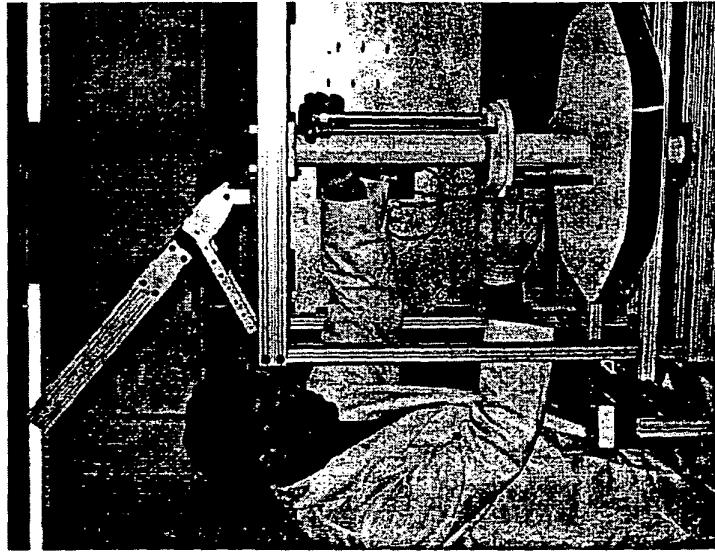
PEM electrolyzers for submarines.

- Fuel cell systems for space flight.
- Solid oxide electrolyzers for Mars exploration.
- Solid oxide electrolyzers for Air Force high altitude aircraft.
- Solid oxide electrolyzers for battlefield oxygen supply.



**Space flight qualified
Oxygen Generator System (OGS)
for the 2001 Mars Lander**

Technical Status



- Cells operated for >2000 hours.
- Three-cell stack operated for >1000 hours, thermally cycled eleven times.
- Five-cell stacks currently in operation.

Intellectual Property

- Ion America presently has 17 patents in the pipeline for
 - interconnect designs
 - electrode formulations
 - electrolyte designs
 - seals
 - stacks
 - systems and applications